Light dark matter
versus astrophysical constraints

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Hints of direct dark matter detection coming from the DAMA, CoGeNT experiments point toward light dark matter with isospin-violating and possibly inelastic couplings. However an array of astrophysical constraints are rapidly closing the window on light dark matter. We point out that if the relic density is determined by annihilation into invisible states, these constraints can be evaded. As an example we present a model of quasi-Dirac dark matter, interacting via two U(1) gauge bosons, one of which couples to baryon number and the other which kinetically mixes with the photon. Annihilation is primarily into "dark neutrinos" that do not mix with the SM, but which could provide an extra component of dark radiation. The model could soon be tested by several experiments searching for such light gauge bosons, and we predict that both could be detected. The model also requires a fourth generation of quarks, whose existence might increase the production cross section of Higgs bosons at the Tevatron and LHC.

Introduction. The DAMA [1] and CoGeNT [2, 3] experiments have presented evidence for light, ~ 10 GeV dark matter (DM), which is at odds with null results from Xenon10 [4], Xenon100 [5] and CDMS [6] for the simplest DM models, and moreover the cross sections needed by DAMA and CoGeNT are at odds with each other. It is very intriguing that a single hypothesis, that DM has isospin-violating interactions with nucleons, resolves the discrepancies between all of the experiments except CDMS [7]-[12]. One further assumption, that the interactions are inelastic, connecting two DM states split by ~ 10 keV, helps to alleviate the tension with CDMS [7, 9] (see also [13]).[1]

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[1]The CRESST experiment [14] reports evidence for light DM with mass 9 GeV at the lower end of their M2 best fit region and cross section $\sigma_n \sim 1.5 \times 10^{-4}$ pb. In an isospin violating model with

Recently we proposed some "minimal models" of hidden sector dark (DM) matter [15] that have the desired properties, and we noted that a number of astrophysical considerations constrain the models very strongly. Essentially, if DM of mass ~ 10 GeV annihilates primarily into any channel other than muons, it is ruled out by constraints from dumping electromagnetic energy into the cosmic microwave background (CMB) [16, 17], Fermi observations of dwarf satellite galaxies [18, 19], or SuperK limits on neutrinos from DM annihilations in the sun [20, 21, 22]. These constraints will tighten as a result of forthcoming data from new experiments like Planck. Moreover the PAMELA constraint on cosmic ray antiprotons excludes 10 GeV DM with an annihilation cross section greater than 0.1 times the standard relic density value if the final state contains quarks that can hadronize [23]. This tension is demonstrated to be rather insensitive to different choices for cosmic ray propagation models and halo models for the $b\bar{b}$ channel in [24]. The only robust particle physics mechanism for evading this tension is if the annihilation is into a pair of bosons that are too light to decay into p-$\bar{p}$ (or do not couple to quarks).

Of course one of these new experiments may find deviations giving positive indirect evidence for light dark matter. But if they instead only tighten the constraints, while direct evidence for light DM persists, we will have a puzzle. One elegant way out is asymmetric dark matter that carries a conserved charge. If the symmetric component of the DM has annihilated away, then the above constraints no longer apply. In the present letter, we wish to point out a different possibility, assuming the DM is symmetric. Namely, if it annihilates primarily into invisible particles, the constraints in question are evaded. While this may seem like a trivial statement, in fact care must be taken to avoid problems from other constraints, such as the number of species during big bang nucleosynthesis (BBN) or too-rapid cooling of supernovae by emission of the new invisible states.[2]

To make these points concrete we will illustrate them in a hidden sector model similar to one presented in [15]. This model achieves isospin violation using a light vector boson B_μ that couples both to gauged baryon number and, and another one Z' that kinetically mixes with the photon. The DM gets inelastic couplings and a small mass splitting through a weak Yukawa interaction with a new Higgs field that breaks the U(1) gauge symmetries. It annihilates dominantly into light "dark neutrinos" via exchange of another new Higgs field, which is also the one primarily responsible for the ~ 10 GeV DM mass. Thus the model is economical, in that most of elements serve for more than one purpose. An interesting feature of this model is that the kinetic mixing of the Z' boson is related to its mass in such a way that it might be discovered in the near future by several proposed experiments aimed at detecting such particles. Moreover because the B boson might mix weakly with Z', it could also be found in the same searches.

$f_p/f_n = -1.5$, this value would increase by a factor of $[\frac{1}{2}(1 + f_p/f_n)]^{-2} = 16$, since O and Ca have equal numbers of protons and neutrons, which is a factor of 13 below the inelastic CoGeNT/DAMA best-fit value for $\sigma_n = 0.03$ pb which we adopt below [11]. This discrepancy is greatly reduced (to a factor of 2) if one adopts the value $\sigma_n = 5 \times 10^{-3}$ pb, corresponding to the best fit with elastic scattering.

[2]We thank D. Spolyar for reminding us about this important constraint.

The Model. Gauged baryon (B) number is anomalous in the standard model, but the anomalies can be canceled by adding a fourth generation of quarks with baryon number ± 1 [25, 26]. If we wish to further couple the DM χ to the associated vector boson B_μ, then to avoid further anomalies it is natural to assume that χ is initially vector-like (Dirac), but a new Higgs boson ϕ that spontaneously breaks some combination of the dark U(1) symmetrires can also couple to χ and render it quasi-Dirac after symmetry breaking. This fits in nicely with the additional preference that the DM interactions with nuclei should be inelastic. A small ~ 10 keV mass splitting between the two DM components is thus both welcome and natural. But because the preference for inelasticity is weak in global fits to all data [11], we will consider two versions of the model, one elastic and the other inelastic. To get isospin violating couplings of the DM to nucleons, we give the DM an additional U(1) coupling to a vector Z' that kinetically mixes with the photon.

The dark sector field content consists of two Weyl DM components $\chi_{1,2}$ with charges $\pm(g_B, g_{Z'})$ under U(1)$_B \times$U(1)$_{Z'}$, a real singlet Φ, a complex Higgs ϕ' with charge $(0, g'_{Z'})$, another $\tilde{\phi}$ with charge $(\tilde{g}_B, 0)$, and in the inelastic version of the model, a third ϕ with charge $(-2g_B, -2g_{Z'})$ There are also "dark neutrinos" ν_1, ν_2 that carry no gauge quantum numbers. All of the Higgs fields need to get VEVs in order to give masses to the dark sector particles. The interactions are

$$
\begin{aligned}
V &= y_\chi \Phi \chi_1 \chi_2 + y_\nu \Phi \nu_1 \nu_2 + M_\nu \nu_2 \nu_2 + \tilde{g}_B^2 |\tilde{\phi}|^2 B^2 + g_{Z'}'^2 |\phi'|^2 Z'^2 \\
&+ (g_B B_\mu + g_{Z'} Z'_\mu)(\chi_1^\dagger \sigma^\mu \chi_1 - \chi_2^\dagger \sigma^\mu \chi_2) + g_B \bar{N} \slashed{B} N + \epsilon e \bar{p} \slashed{Z'} p \\
&+ \left\{ 4(g_B B_\mu + g_{Z'} Z'_\mu)^2 |\phi|^2 + \tfrac{1}{2} y_\phi (\phi \chi_1 \chi_1 + \phi^* \chi_2 \chi_2), \quad \text{inelastic model} \right\}
\end{aligned}
\tag{1}
$$

where p is the proton, and N is either kind of nucleon. Note that for the elastic version of the model, the last line is omitted, and expressions like $\chi_1 \chi_2$ are shorthand for $\chi_1^T \sigma_2 \chi_2$. The lighter dark neutrino which we will call ν' gets a small mass from the see-saw mechanism once Φ gets a VEV, due to the large bare mass M_ν. The structure of the couplings of Φ can be justified by a discrete symmetry[3] $\chi_1 \to -\chi_1$, $\nu_1 \to -\nu_1$, $\Phi \to -\Phi$. The light dark neutrino mass eigenstate ν' allows the DM to annihilate invisibly via $\chi\chi \to \Phi\Phi$ followed by $\Phi \to \nu'\nu'$. For simplicity we have imposed a second discrete symmetry $\chi_1 \to \chi_2$, $\phi \to \phi^*$ so that there is only a single Yukawa coupling y. When Φ and ϕ get their VEVs, the DM mass eigenstates are $\chi_\pm = \frac{1}{\sqrt{2}}(\chi_1 \pm \chi_2)$ with masses $M_\pm = M_\chi \pm \mu$ where $M_\chi = y_\chi \langle \Phi \rangle$ and $\mu = y_\phi \langle \phi \rangle$.

The gauge bosons B and Z' do not mix with each other in the elastic version of the model, but the VEV of ϕ causes them to do so in the inelastic version. We want to suppress such mixing to avoid having any gauge boson with significant couplings to both baryon and lepton number, since the constraints on such particles are quite severe. (These constraints also place stringent limits on isospin violating dark matter models in which a single vector couples to baryon number and mixes kinetically with the photon.) Ref. [27] shows that a vector that couples to B and has kinetic mixing of $\epsilon = 10^{-3}$

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[3] This symmetry must be softly broken to avoid the cosmological domain wall problem, but such breaking in the potential for Φ does not concern us in the following.

is relatively safe, but one with $\epsilon = 10^{-2}$ is ruled out if its mass is less than 10 GeV. Moreover our determination of the correct amount of isospin violation is simpler if the mixing between B and Z' is negligible so that we can consider these fields to coincide with the mass eigenstates. We will thus assume that $\langle \phi \rangle$ is significantly smaller than $\langle \tilde{\phi} \rangle$ and $\langle \phi' \rangle$. In the mass eigenstate basis, the interaction of χ with B becomes purely off-diagonal: $g_B \bar{\chi}_+ \not{B} \chi_- +$ h.c., written in terms of Majorana-Dirac spinors.

Fitting to CoGeNT/DAMA and relic density. We now consider the constraints arising from direct and indirect detection. (See table 1 for a summary of the results for constraints on all the model parameters.) Comparing the diagrams for χ-n and χ-p scattering, the ratio of DM couplings to neutrons and protons is

$$\frac{f_p}{f_n} = 1 + \frac{g_{Z'} \epsilon e}{g_B^2} \frac{m_B^2}{m_{Z'}^2} \tag{2}$$

We fix $f_p/f_n = -1.53$, as needed to evade bounds from Xenon and to reconcile the DAMA/CoGeNT observations [11]. The overall rates for DAMA/CoGeNT are reproduced by matching the cross section for scattering on neutrons, $\sigma_n = g_B^4 \mu_n^2/(\pi m_B^4)$ to the value 3×10^{-38} cm^2 [11, 15], where the reduced nucleon mass is $\mu_n = 0.84$ GeV if the DM mass is $M_\chi = 8$ GeV. This gives $m_B/g_B = 232.3$ GeV and $m_{Z'}^2/(g_{Z'}\epsilon) = -(79.9 \text{ GeV})^2$.

As described in [15], we can use the above relations between $\{m_B, g_B\}$ and $\{m_{Z'}, g_{Z'}\}$ to eliminate the couplings in terms of the masses when computing the annihilation cross section into standard model particles by the processes $\chi\chi \to BB, Z'Z', BZ' \to f f \bar{f} \bar{f}$ or $\chi\chi \to B, Z' \to f\bar{f}$. For a given choice of ϵ, this results in contours of $\langle \sigma_{\text{ann}} v \rangle$ in the m_B-$m_{Z'}$ plane. By comparing the resulting value of $\langle \sigma_{\text{ann}} v \rangle$ to that required for the standard relic density, we see which ranges of the masses are compatible with annihilation that is subdominantly into visible particles, so that the relic density can be determined by invisible annihilations. The result is given in fig. 1, which shows that for a given value of ϵ, there exists a region where $m_{Z'}$ and m_B are both bounded from above such that annihilation into SM particles is sufficiently suppressed. For a given value of ϵ, we find that the maximum allowed value of $m_{Z'}$ is given by

$$m_{Z'} < \sqrt{\epsilon} \cdot 16.6 \text{ GeV} \tag{3}$$

which corresponds to the horizontal part of the contours showing where $\langle \sigma_{\text{ann}} v \rangle < 0.1 \cdot \langle \sigma_{\text{ann}} v \rangle_0$ in fig. 1. This is the minimum reduction of annihilation into visible particles needed to satisfy the astrophysical constraints. On the other hand, $m_B < 4$ GeV is the bound on m_B regardless of ϵ.

To get the correct relic density, it is convenient to assume that $m_\Phi < M_\chi$ so that $\chi\chi \to \Phi\Phi$ is allowed.[4] In this case we can determine a function of y_χ and m_Φ by demanding that the cross section for $\chi\chi \to \Phi\Phi$ be 3×10^{-26} cm^3/s. The theoretical cross section is given by $\langle \sigma_{\text{ann}} v \rangle = y_\chi^4 f(m_\Phi/M_\chi)/(64\pi M_\chi^2)$, where $f(x) = (1-x^2)^{3/2}/(1-x^2/2)^2$. For $m_\Phi < 0.9 \, m_\chi$, y_χ is in the range 0.076 to 0.11. This implies that $\langle \Phi \rangle \sim 73 - 105$ GeV, since $M_\chi = y_\chi \langle \Phi \rangle \cong 8$ GeV is determined by the fit to CoGeNT/DAMA [11]. We

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[4]If $m_\Phi > M_\chi$, one must compute the annihilation cross section for $\chi\chi \to 4\nu'$.
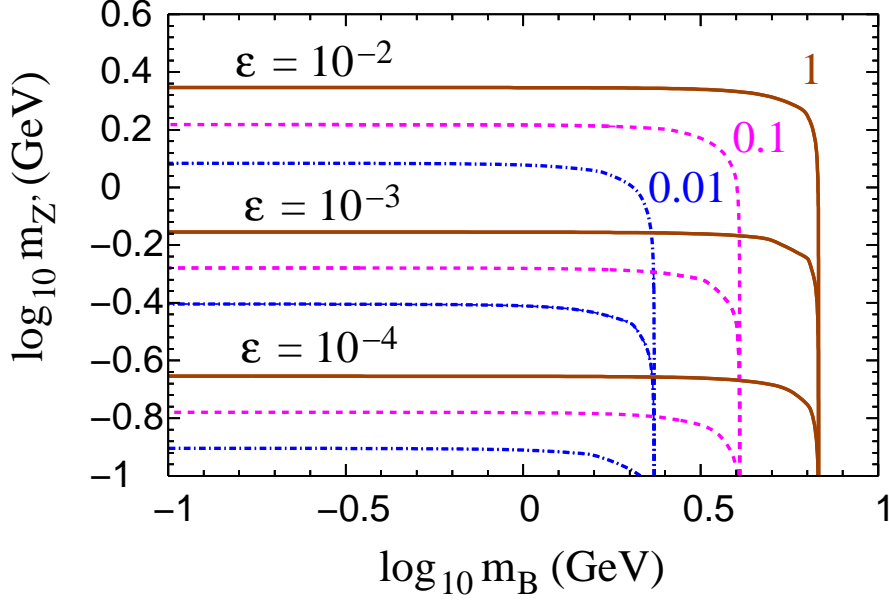
Figure 1: For kinetic mixing $\epsilon = 10^{-2}, 10^{-3}, 10^{-4}$, we show contours in the m_B-$m_{Z'}$ plane where the DM annihilation cross section into visible particles is equal to 1 (solid), 0.1 (dashed) and 0.01 (dot-dashed) times the standard relic density value 1 pb$\cdot c$. The allowed regions are below and to the left of the corresponding contour.

find that the s-channel contribution to $\chi\chi \to \Phi\Phi$, which is controlled by the cubic term in potential for Φ, is smaller than the dominant t-channel contribution by a factor of $m_\Phi^4/(16y_\chi^2 M_\chi^2 \langle\Phi\rangle^2) \ll 1$ in the squared amplitude. Furthermore, annihilation to $\nu'\nu'$ is suppressed because, as we show below, the Yukawa coupling y_ν is much smaller than y_χ.

New Higgs boson parameters. Next we turn to properties of the other new Higgs bosons and Yukawa couplings. For the inelastic version of the model, we require that $g_B g_{Z'} \langle\phi\rangle^2 \ll m_B^2, m_{Z'}^2$ to suppress the gauge boson mixing. If the gauge couplings are of similar size, this implies $\langle\phi\rangle \ll \langle\tilde\phi\rangle, \langle\phi'\rangle$. Since the mass splitting between the DM states is given by $2\mu = 2y_\phi\langle\phi\rangle \cong 10$ keV, having small $\langle\phi\rangle$ helps to explain the smallness of this splitting. For example if $\langle\phi\rangle \sim 10$ GeV, then $y_\phi \sim 10^{-6}$.

The other VEVs $\langle\tilde\phi\rangle$, $\langle\phi'\rangle$, can be be relatively large, if the couplings $\tilde g_B$, $g'_{Z'}$ are small. Using the constraints on (m_B, g_B) and $(m_{Z'}, g_{Z'})$ found above, we have

$$\langle\tilde\phi\rangle = \frac{g_B}{\tilde g_B} \cdot 232 \text{ GeV}, \quad \langle\phi'\rangle = \frac{\sqrt{|g_{Z'}\epsilon|}}{g'_{Z'}} \cdot 80 \text{ GeV} \tag{4}$$

In particular, by choosing $\tilde g_B$ to be smaller than g_B, $\tilde\phi$ can have a larger VEV than the SM Higgs. This helps the model to avoid being marginalized by recent very stringent constraints on the fourth generation of quarks needed for cancellation of the anomaly of gauged baryon number, since $\langle\tilde\phi\rangle$ can contribute to the mass to vector-like 4th generation

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quarks [26]. We discuss this issue further in the final section.

In the potential (1) we have omitted the renormalizable couplings of ϕ and Φ to the standard model Higgs field,[5]

$$\lambda_{\phi h}|\phi|^2 h^2 + \lambda_{\Phi h}|\Phi|^2 h^2 \tag{5}$$

which would give rise to ϕ-h and Φ-h mixing, with the mixing angles

$$\theta \cong \frac{\lambda_{\phi h}\langle\phi\rangle v}{m_h^2 - m_\phi^2}, \quad \Theta = \frac{\lambda_{\Phi h}\langle\Phi\rangle v}{m_h^2 - m_\Phi^2}, \tag{6}$$

where $v = \langle h \rangle = 246$ GeV. Such mixing gives rise to additional interactions between the DM and nucleons by exchange of the new Higgs particles. Because y_ϕ is so small, there is no strong constraint on θ, but Φ exchange is potentially dangerous since it would perturb the amount of isospin violation away from the optimal value if its effect on χ-nucleon scattering was comparable to that of the gauge boson exchange. Moreover the inelastic feature would be spoiled by strong Φ exchange since the couplings of Φ are not off-diagonal in the χ mass eigenbasis. To avoid this problem we require that

$$\frac{y_\chi \Theta\, y_n}{m_\Phi^2} \ll \frac{g_B^2}{m_B^2} \tag{7}$$

where $y_n \cong 0.3\, m_n/v$ is the coupling of h to the nucleon (see for example [28]). However using the above values for g_B/m_B and y_χ, this is not very stringent; even for $m_\Phi = 4$ GeV it only constrains $\Theta \ll 2.6$, which far weaker than direct experimental constraints on the mixing of such a light Higgs boson, $\Theta < 10^{-2}$ [29].

Constraints on dark neutrinos. Finally we come to the properties of the light dark neutrino, ν'. It was last produced when the temperature of the universe was $O(m_\Phi)$ from the decays $\Phi \to \nu'\nu'$. If $m_\Phi \sim 1$ GeV, this occurred before the QCD phase transition, and the relic density of ν' is suppressed by a factor of ~ 60, the reduction in the number of degrees of freedom in the thermal plasma. This means that cosmological upper bounds on the sum of neutrino masses, which we take to be 0.3 eV (see [30] for a review), are relaxed by a factor of ~ 22 (using the fact that ordinary neutrinos have a number density that is 4/11 that of photons), giving the bound $m_{\nu'} < 6.5$ eV. This puts an upper limit on y_ν,

$$y_\nu \lesssim 3.5 \times 10^{-5} \left(\frac{M_\nu}{1 \text{ TeV}}\right)^{1/2} \tag{8}$$

Because of the dilution of the ν' number density, there is no constraint from its contribution to the Hubble rate during BBN.

A potentially serious constraint arises from the fact that ν' can be produced in supernovae by the nucleon collisions $NN \to NN\nu'\nu'$ (via virtual Φ emission), causing

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[5] ϕ' of course also has such couplings but is unimportant to our discussion because it does not couple to the DM.

them to cool more quickly than observed in SN 1987A. A similar process in which sterile neutrinos are produced by vector current couplings to nuclei was considered in ref. [31]. (The vector coupling is expected to give similar results to our scalar coupling [32].) Adapting these results to the present case, we find that

$$\frac{\sqrt{\Theta\, y_n\, y_\nu}}{m_\Phi} \lesssim \frac{1}{100\ \text{TeV}} \tag{9}$$

Using our fiducial values $m_\Phi \sim 1$ GeV and $y_\nu \sim 3.5 \times 10^{-5}$, this translates into the constraint $\Theta < 2 \times 10^{-3}$, which puts the mixing of Φ with h out of experimental reach [29] unless y_ν is taken to be smaller.

For DM to annihilate invisibly, the decay channel $\Phi \to \nu'\nu'$ must dominate over decays into standard model channels like $\mu^+\mu^-$[6] due to the mixing Θ, implying that $y_\nu^2 \gg (\Theta y_\mu)^2$ (where $y_\mu = 4.3 \times 10^{-4}$ is the SM Yukawa coupling of μ). If Θ saturates its direct experimental upper bound of 10^{-2} and y_ν saturates (8) then this criterion is satisfied even for M_ν at the TeV scale. Heavier decay products can be accommodated by a modest increase in M_ν.

Interestingly, positive evidence for an additional species of dark neutrinos has come from recent CMB data [33]. If m_Φ is below the QCD scale, the decays $\Phi\nu'\nu'$ can occur sufficiently late for ν' to have as large an abundance as the SM species. Smaller values of m_Φ would naturally be correlated with lower ν' masses since both are related to $\langle\Phi\rangle$. These neutrinos must be sufficiently light to constitute an extra component of radiation before recombination, rather than being an extra component of the dark matter.

Discussion. We have presented what we believe to be the simplest model of symmetric light dark matter that has the potential for explaining the tentative evidence from CoGeNT and DAMA[7] while robustly evading stringent astrophysical constraints that may soon exclude all such models unless the dominant DM annihilations are into invisible particles. The isospin violating interactions between DM and nucleons are mediated by light vector bosons B of gauged baryon number and a Z' that has kinetic mixing ϵ to the photon.

The model is strongly constrained, and predicts a maximum value of $m_{Z'}$ for each value of ϵ (3) to sufficiently suppress the visible annihilation channels, as well as a minimum value of m_B to suppress the gauge boson mixing angle. There are shown in fig. 2. The region of the $m_{Z'}$-ϵ plane to the left of the solid line is interesting from the point of view of the proposed Heavy Photon Search (HPS) [34] and DarkLight [35, 36] experiments at Jefferson Laboratory. Fig. 2 shows that these two experiments, as well as the already-running APEX experiment [37], are capable of probing a large fraction of the parameter space predicted by the model. We make the interesting observation that both B and Z' could be discovered by these experiments in the inelastic version of the model, where B has a small mixing θ_B with Z' and thus couples to the electromagnetic current with strength $\epsilon\theta_B$.

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[6] in general, the heaviest SM fermions that can be produced by Φ decay, keeping in mind that $m_\Phi < M_\chi \cong 8$ GeV

[7] from footnote 1, it appears that that CRESST can only be made compatible with these if the requirement of inelastic scattering is dropped

parameter	value	constraint
$-\epsilon$	< 0.03	fig. 2
m_B	< 4 GeV	fig. 1
$m_{Z'}$	$< \sqrt{\epsilon} \cdot 16.6$ GeV	eq. (3)
g_B	$m_B/(232$ GeV$)$	eq. (2), σ_n
$g_{Z'}$	$-\epsilon^{-1} m_{Z'}^2/(80$ GeV$)^2$	eq. (2), σ_n
$\langle\phi\rangle$	$\ll \langle\phi'\rangle, \langle\tilde\phi\rangle$	gauge boson mixing
$\langle\tilde\phi\rangle$	$(g_B/\tilde g_B) \cdot 232$ GeV	eq. (4)
$\langle\phi'\rangle$	$(\sqrt{|g_{Z'}\epsilon|}/g'_{Z'}) \cdot 80$ GeV	eq. (4)
$\langle\Phi\rangle$	$73 - 105$ GeV	M_χ/y_χ
y_χ	$0.076 - 0.11$	M_χ, relic abundance
y_ϕ	$\sim 10^{-6}$	χ mass splitting
y_ν	$\lesssim 3.5 \times 10^{-5}$	$m_{\nu'}$, $\tilde\phi \to \nu'\nu'$
M_ν	$\sim$ TeV	$m_{\nu'}$

Table 1: Summary of allowed values of parameters of the model (1), and the corresponding constraints which determine them.

Another experimental test of the model will come from the requirement of a fourth generation of quarks carrying exotic baryon number ± 1 in order to cancel gauge anomalies of B [25, 26]. Because the field $\tilde\phi$ that spontaneously breaks B can have a larger VEV than the SM Higgs, it can increase the mass of vector-like exotic quarks without requiring them to have very large Yukawa couplings. Otherwise, such exotic quarks would be difficult to hide from current collider searches. The strongest constraint comes from the enhancement by a factor of 9 of Higgs boson production by gluon fusion [38] due to the extra generation. Tevatron and ATLAS have recently produced similar preliminary upper limits of $m_h < 124$ GeV [39] and $m_h < 120$ GeV [40] at 95% c.l. through the decay channel $h \to W^+W^-$. Our model avoids these constraints to the extent that $\langle\tilde\phi\rangle = (g_B/\tilde g_B) \cdot 232$ GeV can exceed the SM Higgs VEV. Barring a large hierarchy between these gauge couplings, it is unnatural to make $\langle\tilde\phi\rangle$ very large, so one may anticipate a softening of this constraint rather than completely evading it. In addition, the new Higgs boson ϕ can have large mixing with the SM Higgs, which would lead to further softening of the constraint.

The model we have presented ties current hints for light dark matter to light vector boson searches, Higgs physics, fourth generation quarks, and the cosmology and astrophysics of sterile (dark) neutrinos. Even if this particular model should be ruled out by future data, the idea of invisibly annihilating dark matter may prove useful if its mass is at the 10 GeV scale.
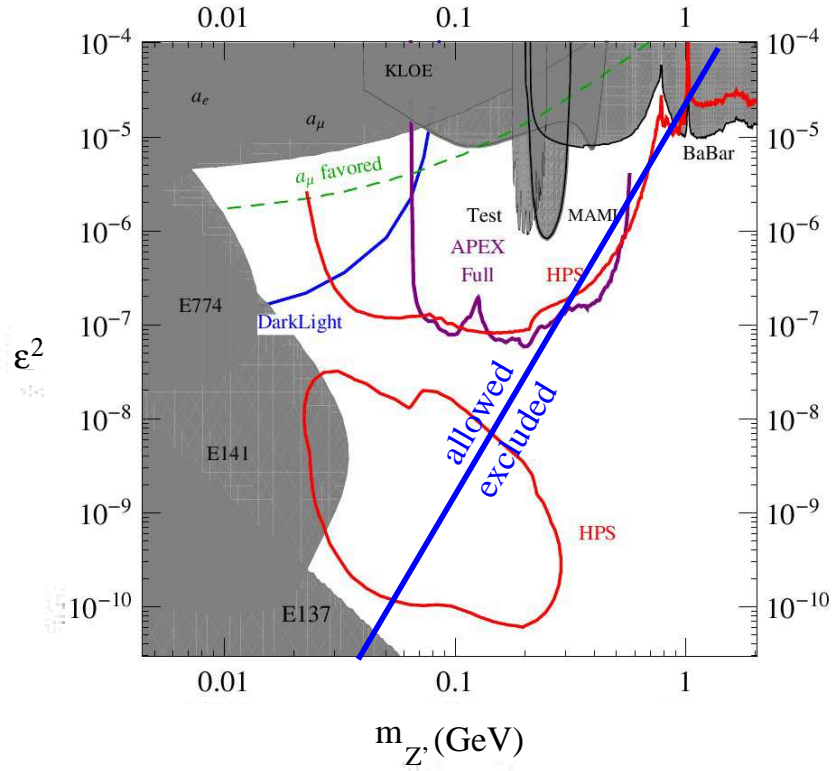
Figure 2: Solid (blue) line shows the maximum allowed value of $m_{Z'}$ (eq. (3)) in the dark matter model for a given value of ϵ, in the $m_{Z'}$-ϵ^2 plane; dark regions are already excluded by various searches for light vector bosons, and light circumscribed regions are targeted by upcoming experiments. Background figure courtesy of R. Essig.

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